Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 88-93

Aluminium Self Piercing Riveted Connections: Effect of Pre-straining and Natural Aging on the Mechanical Behaviour

N-H. Hoang[1,2,*], M. Langseth[1,2], R. Porcaro[1,3], A-G. Hanssen[1,2,4]

[1] Structural Impact Laboratory (SIMLab), Centre for Research-based Innovation, and [2] Department of Structural Engineering, Norwegian University of Science and Technology, N-7491 Trondheim, Norway
[3] SINTEF Materials and Chemistry, N-7465 Trondheim, Norway
[4] Impetus Afea AS, Norway

Abstract: In the present paper, the challenges of the self-piercing riveting technology when using an aluminium rivet to join two aluminium plates have been studied. The study has shown that aluminium self-piercing rivets can be used to join aluminium plates; however the softening of the plate material was needed in order to get a proper connection. The softening may be obtained by a solid heat treatment, resulting in so-called W temper. The effects of the natural age-hardening of plates in W temper to be joined, and the pre-straining of plates due to the riveting process were investigated through an extensive material test programme. Tensile tests after 3 days of natural aging of the pre-deformed materials in alloy AA6063-W revealed that the plastic pre-deformation in W temper leads to a lowering of the reloaded stress-strain curves, compared to the 'virgin' curve (i.e. curve without plastic pre-strain) at the same level of plastic strain. Experimental and numerical investigations on the mechanical behaviour of a single riveted connection were also carried out. The effect of the riveting process and natural aging were included in a user-defined constitutive model in the LS-DYNA code for numerical analyses. The comparison between numerical and experimental results in terms of force-displacement curves showed that it is necessary to consider the combined effect of the pre-straining and the natural aging of the plates in order to predict the mechanical behaviour with reasonable accuracy.

* *Corresponding author. Address: Structural Impact Laboratory (SIMLab), Centre for Research-based Innovation, Norwegian University of Science and Technology, N-7491, Trondheim, Norway. Tel: +47 73 59 47 83*
E-mail address: hoang.nguyen-hieu@ntnu.no

1. Introduction

Self-piercing riveting (SPR) is nowadays one of the most important cold joining technologies in lightweight structures. Especially in the automotive industry, the knowledge obtained on steel riveted connections ([1-7]) has consolidated a firm position of the SPR technology besides the welding technique. However, the combination of steel rivets and an aluminium car body makes recycling a challenge, and aluminium rivets have thus been launched as an alternative.

The present paper reviews the challenges of this cold joining technology when using an aluminium rivet to join two aluminium plates. The review was based on the work of Hoang et al. [8], and it showed that the softening of plates by solid heat treatment prior to the riveting process, resulting in W temper, was needed to have a proper connection. The temper W is a non-stable condition, and the properties of a plate in W-temper depend on the natural aging time. Moreover, the riveting process also results in an evolution of some internal variables, e.g. the effective plastic strain, within the plates and the rivet. Thus, the interaction between the results from the riveting process and the subsequent natural age-hardening of the plates to be joined needs to be understood in order to have a better insight into the mechanical behaviour of an aluminium SPR connection.

In the present study, material tests were carried out in order to understand the consequence of the pre-straining of the plates in alloy 6063-W and the subsequent natural aging. Experimental and numerical investigations on the mechanical behaviour of a single riveted connection were also carried out. The riveted connection was obtained by using a rivet in alloy 7278-T6 to join two plates in alloy 6063-W. Numerical 'through-process' analysis of the mechanical behaviour of two riveted connections was performed by using the explicit solver in the finite element code LS-DYNA. Moreover, a user-defined material model was created in order to take into account the combined effect of the pre-straining of the plates in temper W due to the riveting process and the subsequent natural age-hardening on the final mechanical behaviour. Finally, numerical and test results were compared in terms of force-displacement curves.

2. Self-piercing riveting process using an aluminium rivet

Hoang et al. [8] investigated the self-piercing riveting of two identical aluminium plates by using an aluminium rivet. They found by investigation of the cross-section of the riveted joints that a rivet compression and a small mechanical interlock occured when the aluminium rivet strength was close to that of the plate material, see Fig. 1b and Fig. 1c. Using a high-strength aluminium rivet eased the riveting process; however, the risk of rivet fracture became then imminent, see Fig. 1d.

In order to avoid these defects and to obtain good riveted joints, the softening of the plates to be joined might be necessary prior to the riveting process. The softening of the plates can be achieved by local heating or a solid heat treatment of the aluminium plates. As shown in Fig. 2a and Fig. 2b, a proper connection was obtained by using high-strength aluminium alloys as rivet material together with the solid heat treatment of the plate material, resulting in the so-called W temper. Moreover, the tests showed that using a FM die can ease the SPR process better than using a DZ die [8]. Thus, in addition to the adjustment of the strength of the rivet material to that of the plate material, the die geometry can also be optimised to deliver a better SPR connection.

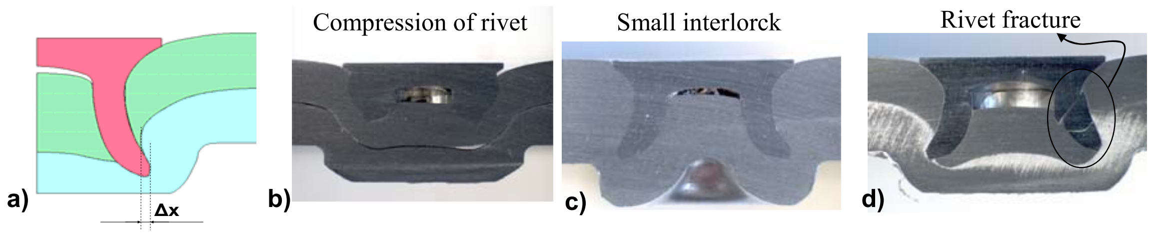

Fig. 1: Joining of aluminium plates by using an aluminium rivet, a) definition of the mechanical interlock, b) compression of the rivet, c) small interlock, d) fracture in rivet

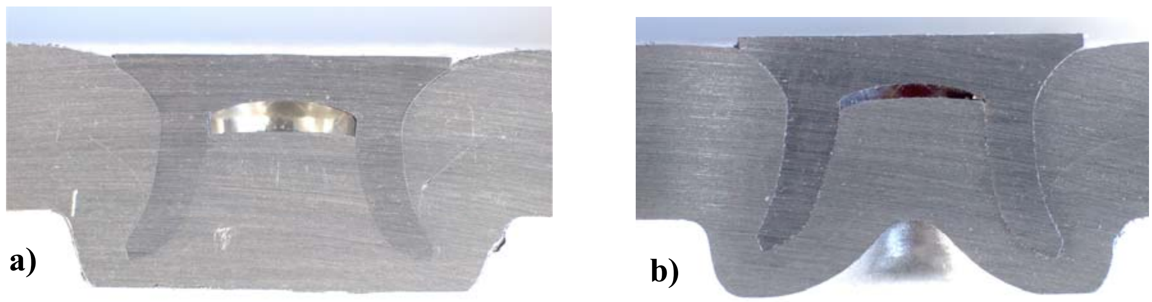

Fig. 2: Cross-sections of proper riveted connections by using aluminium rivets in alloy 7278-T6, a) FM die, b) DZ die.

3. Influence of the pre-straining and natural aging of the plate material

The softening of the plate material by solid heat treatment, resulting in the so-called W temper, was employed in order to obtain a proper riveted connection. However, the temper W is a non-stable condition, and the properties of W-temper depend on the natural aging time. Moreover, the riveting process also results in an evolution of some internal variables, e.g. the effective plastic strain, within the plates and the rivet. In order to understand the combined effect of both the stress-strain distribution in the rivet and the plates, and the natural age-hardening of the aluminium plates in W-temper, the following material test programme which is illustrated in Fig. 3 was carried out. The commercial alloy AA6063 was chosen for the investigation.

During the test programme, 12 tensile specimens in alloy AA6063 were machined from extruded profiles, and subsequently heat treated to obtain the W temper, before being uniaxially stretched to different levels of plastic deformation, see Fig. 3, and Table 1. Three repetitive tests were carried out for each pre-strain level. All the pre-stretched specimens were then naturally aged at room temperature. Here, only 3 days of natural aging was considered for all the pre-strain levels. After the natural aging phase, the pre-stretched specimens were reloaded in the same uniaxial direction until failure occurred. All the pre-stretching and reloading tests were performed at room temperature, at a quasi-static strain rate, i.e. approximately $10^{-3}s^{-1}$. It is to be noted that both the pre-stretching and subsequent uniaxial tensile tests samples were aligned with the extrusion direction of the alloy.

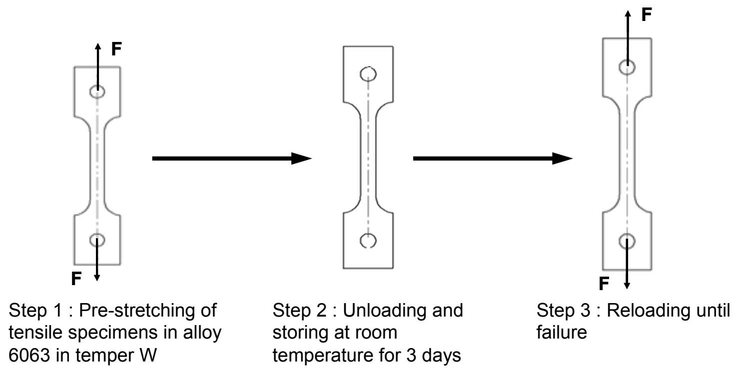

Fig. 3: Material testing procedure

Pre-strain level (%)	Pre-strain ID
0	S_0
5.00	S_1
10.00	S_2
15.70	S_3

Table 1: Definition of pre-strain by pre-stretching

The properties of the alloy 6063 in W temper as function of age-hardening time are presented in terms of true stress-strain curves in Fig. 4a. It can be seen that the natural aging has a significant influence not only on the yield stress but also on the hardening of the temper W.

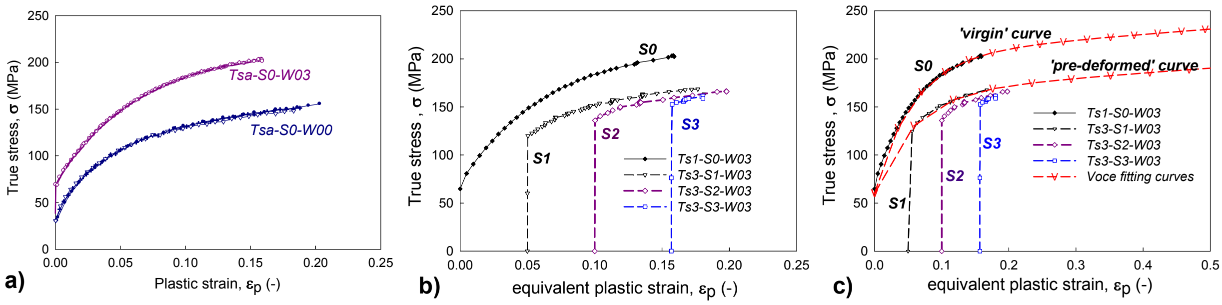

Fig. 4: Material properties, a) Stress-strain curves of alloy 6063W at different aging times, b) Tension-tension results from tensile testing of pre-stretched material in temper W-10min (denoted by W00) and subjected to natural aging for 3days (denoted by W03), c) Representative stress-train curves of 'virgin' and 'pre-deformed' materials

In order to study the influence of the pre-straining in temper W-10 min on the material properties after 3 days of aging (W-03), all the true stress-plastic strain curves were plotted as function of the pre-strain values along with the 'virgin' curve, i.e. the curve without pre-strain, Fig. 4b. It can be seen that the flow stress was much lower compared with the stress of the 'virgin' curve at the same equivalent strain. Moreover, it is of interest to notice that all the stress-strain curves of the pre-strained material seem to converge to the same curve at larger plastic deformations after a transient phase, Fig. 4c. This curve is used to distinguish the material associated with the combined effect of pre-straining and natural aging, named 'pre-deformed' material, and the 'virgin' material which are associated with only the aging effect, see Fig. 4c. The two curves were then fitted with the Voce hardening rule given by Eq.1, where σ_0 is the reference yield stress, $\bar{\varepsilon}$ is the effective plastic strain, and Q_i and C_i are Voce work hardening parameters.

$$\sigma_Y = \sigma_0 + \sum_{i=1}^{2} Q_i \left(1 - \exp(-C_i \bar{\varepsilon})\right) \qquad \text{(Eq.1)}$$

4. Analyses of the mechanical behaviour of aluminium self-piercing riveted connections

The previous section demonstrated the interaction between two effects: pre-straining in W temper, and natural aging of alloy AA6063. In order to evaluate how the riveting process and the subsequent natural aging of the plates influence on the mechanical behaviour of a riveted connection, an experimental and numerical investigation were carried out.

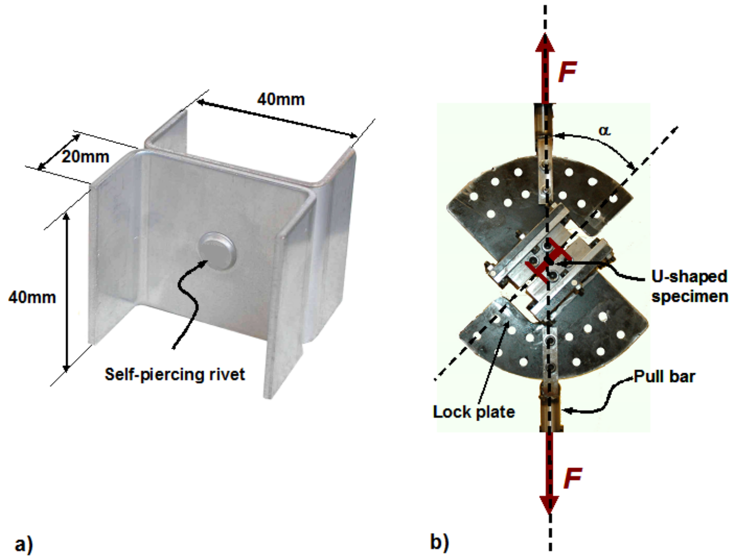

Fig. 5: a) Geometry of U-shaped specimens, and b) Testing facility

The riveted connection under question was obtained by the heat treatment of two identically U-shaped components in alloy AA6063 into temper W, and subsequently joined together using a self-piercing rivet in alloy AA7278-T6, see Fig. 5a. The U-shaped components were cut from extruded profiles with a wall thickness of 1.88mm. The rivet and dies were fabricated following the Boellhoff standard [8]. The riveted U-shaped coupons were then stored at room temperature for 3 days before testing the mechanical capacity under pure pull-out loading condition by using the test facility shown in Fig. 5b. Details of the test facility can be found in [4]. Tests were performed with a velocity of approximately 0.025mm/s. Force-displacement curves were recorded during the tests and will be compared with numerical analyses.

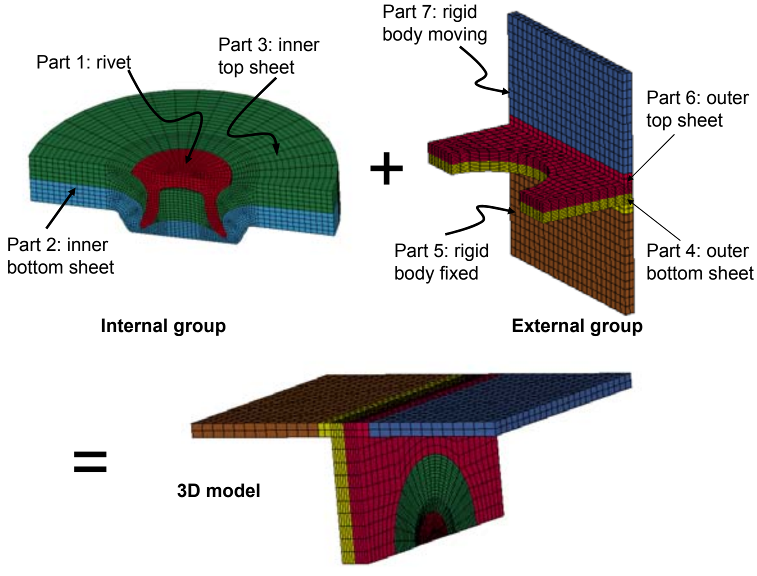

Fig. 6: A half of 3D model of the riveted connection

The numerical investigation was carried out by using a 3D model which consists of an internal group, and an external group, see Fig. 6. The external group is supposed not to be influenced by the riveting process, and was created based on the geometry of the U-shaped specimen shown in Fig. 5a. In order to take the riveting process effects into account in the numerical 3D analyses, a mapping process which is described in Fig. 7 was used. Here, the stresses and strains within the rivet and plates obtained from a 2D analysis of the riveting process [8] were mapped into the 3D model. Finally, the internal and external groups were merged together. All the numerical simulations were carried out using the explicit solver in the finite element code LS-DYNA.

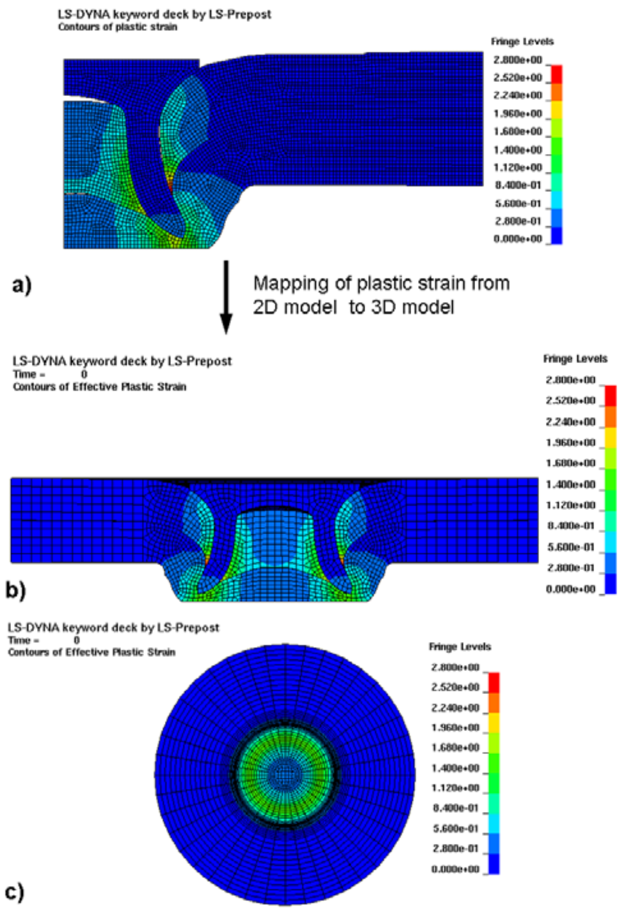

Fig. 7: Mapping process: a) results from the 2D riveting process analysis with fine mesh, b) 3D model generated with a coarser mesh including the stress-strain distribution from the 2D analysis, and c) a view from bottom of the 3D model – all the elements situated on the same circumference and z-coordinate have the same value of the initial stress and strain

Based on the previous investigation, two different modelling approaches accounting for the riveting process effects and the natural aging of the material in W temper on the mechanical behaviour of a riveted joint were investigated in the present study, Fig. 8:

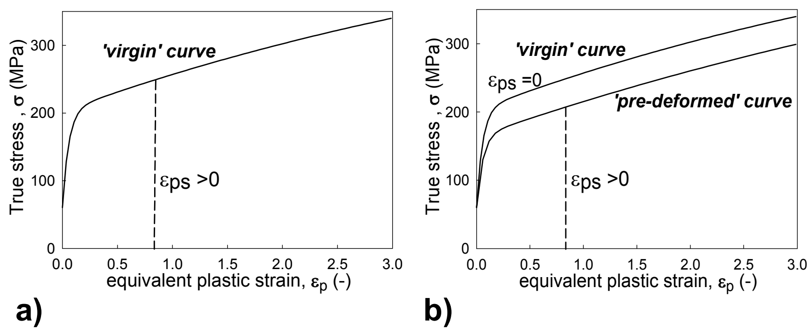

Fig. 8: Illustration of two different approaches for the modelling: a) approach 1, b) approach 2.

(1) In the first approach the pre-straining in W temper was assumed to have no influence on the evolution of the natural aging of the material, i.e. the reloaded curve of the pre-strained material in W temper was assumed to rejoin the ‘virgin’ curve after reloading. More clearly, only the ‘virgin’ curve from Fig. 4c was used in combination with the stress-strain distribution data, see Fig. 8a.

(2) In the second approach the pre-straining was assumed to have effect on the evolution of the natural aging of the material, i.e. both the ‘virgin’ curve and the ‘pre-deformed curve from Fig. 4c were used in combination with the stress-strain distribution data, see Fig. 8b.

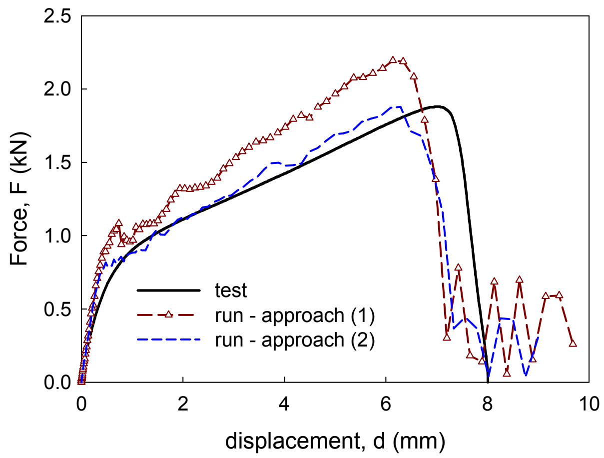

Fig. 9: Comparison between experimental and numerical force-displacement curves of aluminium riveted connections under pure pull-out loading condition with different modelling strategies

A user-defined material model which allows the coupling of the pre-strained and natural age-hardened properties was used. Fig. 9 shows the results for the U-shaped specimen under investigation for the pure pull-out loading condition when using the two approaches. As illustrated, the force-displacement curve obtained by approach (2) was in a good agreement with the experimental data. However, approach (1) seems to be physically unrealistic, and the predicted force level was overestimated in comparison with the experimental one. It is thus very important to consider this combined effect in order to have a better insight into the behaviour of riveted connections.

5. Conluding remarks

The following concluding remarks can be drawn from the present study:

- The pre-straining of alloy 6063 in W temper has a noticeable influence on the material flow curves after 3 days of natural aging.
- There is a combined effect between the pre-straining and the natural aging. More clearly, this combined effect lowers the stress-strain curve of the 'pre-deformed' material in comparison with the 'virgin' material.
- The numerical analyses carried showed that the process effects including the natural age hardening have to be taken into account in order to get good predictions compared with the test data.

References:

[1] Abe, Y., T. Kato, and K. Mori, *Joinability of aluminium alloy and mild steel sheets by self piercing rivet.* Journal of Materials Processing Technology, 2006. 177(1-3): p. 417-421.

[2] Abe, Y., T. Kato, and K. Mori, *Self-piercing riveting of high tensile strength steel and aluminium alloy sheets using conventional rivet and die.* Journal of Materials Processing Technology, 2009. 209(8): p. 3914-3922.

[3] Mori, K., et al., *Plastic Joining of Ultra High Strength Steel and Aluminium Alloy Sheets by Self Piercing Rivet.* CIRP Annals - Manufacturing Technology, 2006. 55(1): p. 283-286.

[4] Porcaro, R., et al., *Joining of aluminium using self-piercing riveting: Testing, modelling and analysis.* International Journal of Crashworthiness, 2004. 9: p. 141-154.

[5] Porcaro, R., et al., *Self-piercing riveting process: An experimental and numerical investigation.* Journal of Materials Processing Technology, 2006. 171(1): p. 10-20.

[6] Porcaro, R., et al., *The behaviour of a self-piercing riveted connection under quasi-static loading conditions.* International Journal of Solids and Structures, 2006. 43(17): p. 5110-5131.

[7] Porcaro, R., et al., *Crashworthiness of self-piercing riveted connections.* International Journal of Impact Engineering, 2008. 35(11): p. 1251-1266.

[8] Hoang, N.H., et al., *Self-piercing riveting connections using aluminium rivets.* International Journal of Solids and Structures, 2010. 47(3-4): p. 427-43